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Dust and Ionized gas in Elliptical Galaxies

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Abstract: Results from *IRAS* and recent X-ray and optical surveys are reviewed to discuss the properties and nature of the interstellar medium in elliptical galaxies.

As to the dust component, there is a strong contrast with the situation among spiral galaxies in that masses of dust in ellipticals as derived from optical extinction are an order of magnitude *lower* than those derived from *IRAS* data. I find that this dilemma can be resolved by assuming an extra, extended, *diffusely distributed component* of dust which is not detectable in optical data.

Bona-fide global correlations among ISM components —and between ionized gas, dust, and global (stellar) properties of ellipticals— are hard to find, which most probably reflects an external origin of dust and ionized gas in ellipticals.

A strong correlation is found, however, between the Hα+[N II] luminosity and the optical luminosity within the region occupied by the ionized gas, which suggests hot (post-AGB and/or blue HB) stars within the old stellar population being a dominant source of ionization of the gas.

1. Introduction

Our understanding of the nature of the interstellar medium (ISM) in elliptical galaxies has undergone a radical change from the consensus that prevailed only a dozen of years ago. Recent advances in instrumental sensitivity across the electromagnetic spectrum have revealed the presence of a complex, diverse ISM in elliptical galaxies; in fact, the total mass of interstellar gas relative to that of stars in ellipticals is similar to that in spiral galaxies, the main difference being that the dominant gaseous component in ellipticals is heated to the virial temperature, $\sim 10^7$ K, radiating at X-ray wavelengths. Smaller, varying quantities of H I, CO, ionized gas, and dust have been detected in many ellipticals as well (*e.g.*, Bregman, Hogg & Roberts 1992).

Unlike the situation in spiral galaxies however, it still remains unclear — and highly controversial— what the correct description of that ISM is, *i.e.*, what the origin and fate of the different components of the ISM are, and in particular whether mergers or cooling-flows dictate the interplay between them (see Sparks, Macchetto & Golombek 1989; de Jong *et al.* 1990; Sparks 1992; Fabian, Canizares and Böhringer 1994; Goudfrooij *et al.* 1994b (hereafter G+94b).

The first direct, unambiguous evidence for the common presence of cool ISM in ellipticals was presented by Jura *et al.* (1987) who used *IRAS* ADDSCANs and found that $\gtrsim 50\%$ of nearby, bright ellipticals were detected at 60 and 100 μm. Implied dust masses were of order $\sim 10^4 - 10^6$ M$_\odot$*. Although the finding that ellipticals contain dust is not so surprising by itself —after all, dust grains are a natural product of ongoing stellar evolution—, the dust masses observed in many giant ellipticals is in fact curiously high: dust grains are destroyed within only 10^6–10^7 yr by thermal sputtering within the hot gas where the typical gas pressure $nT \sim 10^5$ cm^{-3}K (Draine & Salpeter 1979).

The dust component of the ISM thus represents a potentially crucial diagnostic in establishing the true physical and evolutionary relationships between the different components of the ISM in ellipticals: the mere observed quantities of dust in ellipticals constrain their evolutionary history. Evolutionary constraints set by dust in ellipticals can become yet more significant when combined with morphological and kinematical properties of the dust (cf. Section 2).

The plan of this paper is as follows. I will discuss the dust component(s) present in ellipticals in Section 2. Section 3 will deal with correlations between the different components of the ISM, along with possible implications of observed physical associations of the hot, warm and cold components in selected ellipticals.

2. Origin and Distribution of Dust in Elliptical Galaxies

2.1 Dust found in Optical Surveys

Optical observations are essential for establishing the presence and distribution of dust and gas in ellipticals, thanks to their high spatial resolution. A commonly used optical technique to detect dust is by inspecting color-index (*e.g.*, B–I) images in which dust shows up as distinct, reddened structures with a morphology different from the smooth distribution of stellar light (*e.g.*, G+94b). A strong limitation of optical detection methods (as opposed to measuring far-IR emission) is that only dust distributions that are sufficiently different from that of the stellar light (*i.e.*, dust lanes, rings, or patches) can be detected. Moreover, detections are limited to nearly edge-on dust distributions, which is illustrated by the fact that no dust lanes with inclinations $\gtrsim 35°$ have been detected (cf. Sadler & Gerhard 1985; G+94b). Thus, quoted optical detection rates of dust represent firm lower limits by nature. Since an inclination range $|i| \lesssim 35°$ is equivalent to $\sim$half the total solid angle on the sky, the *true* detection rate should be about twice as high as the measured one (at a given detection limit for dust absorption). The recently measured detection rate of dust in a complete, blue magnitude-limited sample ($B_T < 12$) of elliptical (E) galaxies in the RSA catalog is 41% (G+94b) which means that *the vast majority of ellipticals could harbor dust lanes and/or patches.*

Evidently, at least part of the dust in ellipticals does not follow the spatial distribution of the stars. This finding bears information concerning the dynamics

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* We assume $H_0 = 50$ km s^{-1} Mpc^{-1} in this paper

of this dust, *i.e.*, whether or not its motions are settled in the galaxy potential. This question is, in turn, linked to the intrinsic shape of ellipticals, since in case of a settled dust lane, its morphology indicates a plane in the galaxy in which stable closed orbits are allowed (*e.g.*, Merritt & de Zeeuw 1983). These issues can be studied best in the inner regions of ellipticals, in view of the short dynamical time scale involved, allowing a direct relation to the intrinsic shape of the galaxy. A recent analysis of *nuclear* dust properties in 64 ellipticals imaged with HST has shown that dust lanes are randomly oriented with respect to the major axis of the galaxy (van Dokkum & Franx 1995). Moreover, the dust lane is significantly misaligned with the *kinematic* axis of the stars for almost all galaxies in the sample of van Dokkum & Franx for which extensive stellar kinematics are available*. This means that *even at these small scales*, the dust and stars are generally dynamically decoupled, which argues for the external origin of the dust. This conclusion is strengthened by the decoupled kinematics of stars and gas in ellipticals with *large-scale* dust lanes (*e.g.*, Bertola *et al.* 1988).

2.2 Dust NOT found in Optical Surveys (The Diffusely Distributed Component of Dust)

As mentioned above, dust in ellipticals has been detected by optical as well as far-IR surveys. Since the optical and far-IR surveys yielded quite similar detection rates, one is tempted to conclude that both methods trace the same component of dust. However, this turns out not to work in the quantitative sense: dust masses estimated from the optical extinction are significantly *lower* than those estimated from the far-IR emission (Goudfrooij & de Jong 1995, hereafter GdJ95)**. Quantitatively, the average ratio $<M_{\rm d,\,IRAS}/M_{\rm d,\,opt}> = 8.4 \pm 1.3$ for the 56 ellipticals in their sample for which the presence of dust is revealed by both far-IR emission and optical dust lanes or patches.

This "dust mass discrepancy" among ellipticals is remarkable, since the situation is *opposite* to that among spiral galaxies: Recent analyses of deep multi-color imagery of dust extinction in spiral galaxies (*e.g.*, Block *et al.* 1994) also reveal a discrepancy between dust masses derived from optical and *IRAS* data, *but in the other sense!* In the case of spirals, the discrepancy can be understood since dust temperatures of order 20 K and lower are appropriate to spiral galaxies (*e.g.*, Greenberg & Li 1995), whereas the *IRAS* measurements were quite insensitive to "cold" dust at $T_{\rm d} \leq 25$ K which radiates predominantly at wavelengths beyond 100 μm. Evidently, the bulk of the dust in spiral disks is too cold to emit significantly at 60 and 100 μm, but still causes significant extinction of optical light. Actually, $T_{\rm d} \lesssim 20\,{\rm K}$ is *also* appropriate to the outer parts of ellipticals (Jura 1982; GdJ95), making the apparent "dust mass discrepancy" among ellipticals even more significant.

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* By the way, most of the ellipticals in the archival sample of HST images described by van Dokkum & Franx (1995) that turn out to be dusty were selected to be dust-free based on ground-based observations, rendering the class of genuinely dutch-free ellipticals very rare :–)

** The methods used for deriving dust masses from optical extinction values and from the *IRAS* flux densities at 60 and 100 μm, and the limitations involved in these methods, are detailed upon Goudfrooij & de Jong (1995).

GdJ95 argued that the discrepancy cannot merely be due to orientation effects, since their Fig. 1 shows that the relation between $M_{\rm d,\,IRAS}/M_{\rm d,\,opt}$ and $\cos i$ for ellipticals with regular dust lanes is a scatter plot. This suggests that the dust in the lanes is concentrated in dense clumps with a low volume filling factor. Instead, they postulate an additional, diffusely distributed component of dust, which is therefore virtually undetectable by optical methods. We note that diffusely distributed dust is not unexpected: the late-type stellar population of typical giant ellipticals ($L_B = 10^{10} - 10^{11}$ L$_{\odot}$) has a substantial present-day mass loss rate ($\sim 0.1 - 1$ M$_{\odot}$ yr^{-1} of gas and dust; cf. Faber & Gallagher 1976; Knapp, Gunn & Wynn-Williams 1992) which can be expected to be diffusely distributed. An interesting potential way to trace this diffuse component of dust is provided by radial color gradients in ellipticals. With very few significant exceptions, giant ellipticals show a global reddening toward their centers, in a sense approximately linear with log (radius) (*e.g.*, Goudfrooij *et al.* 1994a, hereafter G+94a). This is usually interpreted as gradients in stellar metallicity, as metallic line-strength indices show a similar radial gradient (*e.g.*, Davies, Sadler & Peletier 1993). However, compiling all measurements published to date on color– and line-strength gradients within ellipticals shows no obvious correlation (cf. Fig. 1), suggesting that an additional process may be (partly) responsible for the color gradients...... so what about dust ?

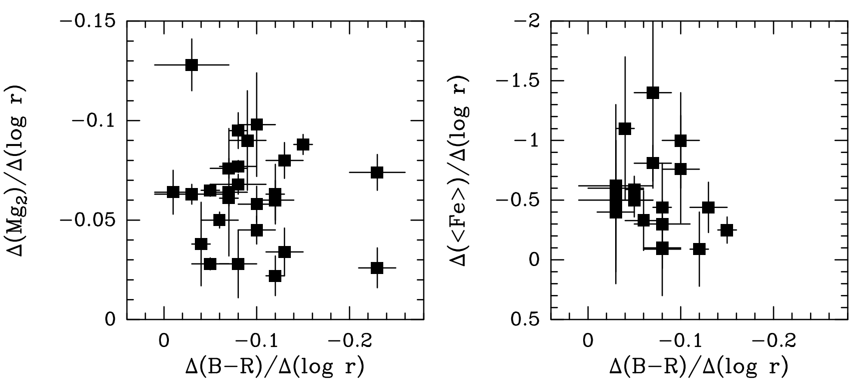

Figure 1. The relation of radial $B-R$ color gradients with radial gradients of the stellar line-strength indices Mg_2 *(left panel)* and <Fe> *(right panel)* for all ellipticals for which both pairs of quantities have been measured to date. Data taken from Peletier (1989), Carollo *et al.* (1993), Davies *et al.* (1993), Carollo & Danziger (1994), and Goudfrooij *et al.* (1994a).

Indeed, recent Monte Carlo simulations of radiation transfer within ellipticals by Witt, Thronson & Capuano (1992) and Wise & Silva (1996) have demonstrated that a diffuse distribution of dust throughout ellipticals can cause significant color gradients. GdJ95 explored the case of an $\rho_{\rm d} \propto r^{-1}$ density distribution for the diffuse dust component (and $\rho_* \propto r^{-3}$ for the stars) in ellipticals, the rationale being that this distribution generates color gradients that are linear with $\log(r)$, as observed (cf. G+94a). Goudfrooij & de Jong evaluated the relation between far-IR-to-blue luminosity ratio and color gradient as a function of total dust optical depth (*i.e.*, the dust mass) for this case. Their

result is shown in Fig. 2a, which shows that color gradients in elliptical galaxies are generally larger than can be generated by a diffuse distribution of dust with $\rho_{\rm d} \propto r^{-1}$. This is as expected, since color gradients should be partly due to stellar population gradients as well. The distribution of the data in Fig. 2a is consistent with a "bottom-layer" color gradient being due to differential extinction by dust. Multivariate analysis of $L_{\rm IR}/L_{\rm B}$, color– and line-strength gradients for a large number of ellipticals should further elucidate this matter.

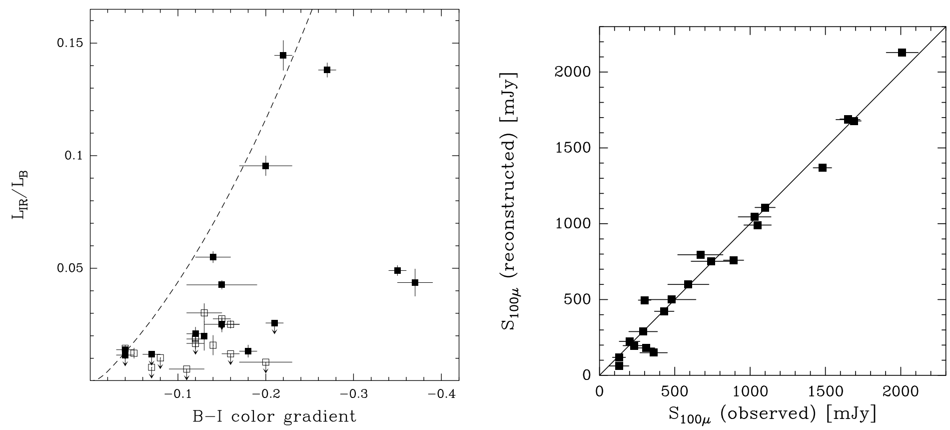

Figure 2. (a, left) The relation of L_{IR}/L_B with $B-I$ color gradients (defined as $\Delta\,(B-I)/\Delta\,(\log r)$) for elliptical galaxies in a complete, blue magnitude-limited sample. Filled squares represent galaxies detected by *IRAS* showing optical evidence for dust, and open squares represent galaxies detected by IRAS without optical evidence for dust. Arrows pointing downwards indicate upper limits to L_{IR}/L_B. The dashed line represents the color gradient expected from differential extinction by a diffuse distribution of dust with $\rho_{\rm d} \propto r^{-1}$ (see text). Figure adapted from Goudfrooij & de Jong (1995). **(b, right)** 100 μm flux densities reconstructed from calculations of dust temperatures in ellipticals versus observed 100 μm flux densities (and their $1\,\sigma$ error bars). The solid line connects loci with "reconstructed = observed". Data taken from Goudfrooij & de Jong (1995).

Another neat feature of the $\rho_{\rm d} \propto r^{-1}$ dust distribution is that it is also *energetically* consistent with the available data. I don't want to go into great detail here to illustrate this point, and refer to the discussion in GdJ95 instead. They computed temperatures of dust grains as a function of galactocentric radius, where the heating is provided by stellar photons (primarily) and energetic electrons in the hot gas (if appropriate), from which they calculated *IRAS* 60 and 100 μm flux densities assuming $\rho_{\rm d} \propto r^{-1}$. This reconstruction reproduces the observed *IRAS* flux densities extremely well (cf. Fig. 2b).

Note that so far, only dust detected by *IRAS* has been considered (*i.e.*, dust with $T_{\rm d} \gtrsim 25\,{\rm K}$); this typically corresponds to dust within the inner few kpc. In reality, the diffuse component of dust in elliptical galaxies may be expected to extend out to where the dust temperature is lower. *ISOPHOT* observations of the "RSA sample" of elliptical galaxies (see G+94a) are presently being analysed, and may reveal this cooler dust component in ellipticals.

Apart from a distribution with $\rho_{\rm d} \propto r^{-1}$ which supposedly accounts for the bulk of the diffusely distributed dust, a small fraction of dust might have

a steeper distribution, being more centrally concentrated. The observational effect of such a dust distribution has been discussed by Silva & Wise (1996); a hint for its presence would be the combination of a flattened surface brightness distribution *and* a steepening of the color gradient within the inner 10^2 pc of a galaxy. Future work on inner color gradients of ellipticals will certainly resolve this issue; currently available color gradients from HST WFPC2 data do *not* show the steepening in the inner 10^2 pc, however (Carollo *et al.*, this meeting).

3. Correlations among various Components of the ISM

3.1 Background

In this Section, I assemble relevant data in the literature available to date in order to study the relationships between the different components of the ISM in ellipticals (including non-thermal radio emission). As to the hot and cold gaseous components, there have been previous efforts to study their relation, most notably: *(i)* Bregman *et al.* (1992) who used the Roberts *et al.* (1991) catalog which includes all literature data through mid-1989, and *(ii)* Eskridge, Fabbiano & Kim (1995) who used the catalog of Fabbiano, Kim & Trinchieri (1992) which comprises all galaxies observed with the *EINSTEIN* X-ray satellite. Since 1991, a wealth of new important data have become available, most notably deep surveys of the ionized gas component in ellipticals.

The existence of this "warm" component of the ISM in ellipticals has been known since a long time. Early spectroscopic observations (e.g., Humason, Mayall & Sandage 1956) first showed the charateristic low-excitation nature of the emission and provided a dectection rate of $\sim 18\%$. More recent spectroscopic surveys of ellipticals (Caldwell 1984; Phillips *et al.* 1986) have pushed the detection rate up to about 50%. In order to appreciate the full spatial extent of the gaseous emission, there have been some half a dozen recent CCD *imaging* surveys of the most prominent low-excitation emission lines, Hα and the [N II] doublet at 6548, 6583 Å: Kim (1989) observed 26 ellipticals and S0s detected by *IRAS*, Shields (1991) observed 46 galaxies detected at X-ray wavelengths, Trinchieri & di Serego Alighieri (1991; hereafter TdSA) observed 13 X-ray-emitting ellipticals which are not at the center of clusters, G+94b observed a optically complete sample of 56 ellipticals from the RSA catalog, Singh *et al.* (1995) observed 7 X-ray-bright ellipticals and S0s, and Macchetto *et al.* (1997) observed a sample of 73 ellipticals and S0s representing a broad variety of X-ray, radio, far-IR and kinematical properties. A potential concern of using Hα+[N II] fluxes from all these different surveys is that some surveys were much deeper than others, which can have quite critical implications due to the fact that many ellipticals feature extended emission at low surface brightness. Hence, I have decided to use the flux from the deepest survey available in case of duplicate Hα+[N II] images of a given object. For the galaxies in which no Hα+[N II] emission was detected, upper limits were calculated from the detection limit to the emission-line surface brightness, assuming a radial extent of 1 kpc. Luminosities have been derived (or converted) according to $D_N-\sigma$ distances from Faber *et al.* (1989).

Due to the page limit of this contribution, I will discuss only a few relations involving the ISM components of ellipticals. A more elaborate account of the statistical analysis will be published in a forthcoming paper.

3.2 Optical nebulosity vs. stellar radiation

There is a weak trend of the Hα+[N II] luminosities with the total B-band luminosities of the galaxies (cf. Fig. 3a), although it is clear that there are a lot of luminous ellipticals in which no sign of ionized gas is found; furthermore, the trend is largely due to the `[distance]`^{2} term in the luminosities, since the trend disappears largely in a flux-flux plot (Fig. 3b).

A much more evident correlation is found between the Hα+[N II] luminosities and the B-band luminosity emitted within the region occupied by the line-emitting gas* (Fig. 3c; see also Macchetto *et al.* 1997). This correlation does persist in a flux-flux plot (Fig. 3d). Taken at face value, this correlation suggests a stellar origin for the ionizing photons, in line with the recent result of Binette *et al.* (1994) who found that post-AGB stars within the old stellar population of ellipticals provide enough ionizing radiation to account for the observed Hα luminosities and equivalent widths. Following the prescriptions of Binette *et al.*, predicted Hα luminosities have been calculated for the current collection of galaxies. The result is $\mathrm{L}_{\mathrm{H}\alpha,\,\mathrm{obs}}/\mathrm{L}_{\mathrm{H}\alpha,\,\mathrm{pred}} = 1.4 \pm 0.6$, which renders the stellar origin of ionizing photons quite plausible *in general.* Of course, this doesn't entirely exclude the possibility of ionization by an active nucleus, internal shocks, or electron conduction in hot gas in individual cases. Line-ratio studies of a significant number of ellipticals are currently being conducted, which can be expected to give important clues in this respect.

3.3 Optical nebulosity vs. radio continuum emission

Ellipticals typically exhibit radio continuum fluxes which are much higher than the strong correlation between radio continuum and far-IR fluxes among spiral and S0 galaxies would predict (e.g., Bregman *et al.* 1992), and therefore thought to be primarily of nonthermal origin, powered by an active nucleus. If the optical nebulosity in ellipticals would also be powered primarily by active nuclei, the Hα+[N II] fluxes would be expected to correlate with the radio continuum fluxes. Such a correlation is found, in fact, for powerful radio ellipticals of the Fanaroff-Riley (FR) II class (Baum & Heckman 1989). Radio data at 6 cm wavelength have been taken from the literature for the ellipticals with available Hα+[N II] data. A plot of Hα+[N II] luminosity vs. 6 cm radio power is shown in Fig. 3e; both quantities have been divided by the B-band luminosity to remove the distance effect. Although there is a weak trend for more powerful radio galaxies to have more luminous optical nebulosity, the scatter in the plot is large. In fact, any line-emitting galaxy with a given $L_{\mathrm{H}\alpha+[\mathrm{N\,II}]}/L_B$ ratio does not seem to "know" about its radio-to-optical luminosity ratio. Thus, active nuclei do

* defined as a circle centered on the galaxy center, and with radius equal to $\sqrt{ab}$, where a and b are the semi-major and semi-minor axis of the area occupied by the line-emitting gas, respectively.

not seem to be a significant source of ionizing photons for gas in a "normal" elliptical (there are no powerful FR-II type radio galaxies in this sample).

3.4 Optical nebulosity vs. hot ISM

Previous studies of ellipticals have produced ambiguous conclusions concerning possible relationships between the optical nebulosity and the X-ray-emitting gas components. Shields (1991) found essentially *no* correlation, whereas TdSA found that —on average— galaxies with a larger content of hot gas also have more powerful line emission, albeit with considerable scatter. Both studies used an X-ray-selected sample; their different result is possibly partly due to different observational flux thresholds. The result of adding the new data obtained after 1991 is depicted in Fig. 3f, which shows the relation of the Hα+[N II] luminosities with the ratio of X-ray-to-B-band luminosities, L_X/L_B. The quantity L_X/L_B has been used here rather than L_X to eliminate the X-ray lumionosity due to discrete (stellar) sources which scales linearly with B-band luminosity, so that L_X/L_B is a measure of the hot gas content; the dashed line in Fig. 3f depicts the threshold in L_X/L_B above which the discrete component is supposedly negligible so that L_X/L_B should scale with hot gas content (cf. Kim *et al.* 1992).

A glance at Fig. 3f reveals a correlation. However, a large scatter is present, and there are a number of galaxies with high L_X/L_B that are weak Hα+[N II] emitters, and several ellipticals that are bright in Hα+[N II] are weak X-ray emitters. In other words, the nebulosity/hot gas connection is certainly not as simple as the standard cooling flow theory (*e.g.*, Fabian *et al.* 1991) would predict. In fact, it seems advisable to study this connection on a galaxy-by-galaxy basis rather than globally (for a whole sample). For example, recent individual studies of X-ray-bright ellipticals involving optical and ROSAT HRI imaging show that the line-emitting filaments are physically associated not only with local peaks in the X-ray emission (as predicted in the cooling-flow theory), *but also with dust lanes* (e.g., NGC 4696 [Sparks *et al.* 1994]; NGC 5846 [Goudfrooij & Trinchieri 1997]). This argues against the cooling-flow theory: While pressures in central regions of a cooling flow ($nT \sim 10^5 - 10^6$ cm^{-3} K) are high compared with e.g., average pressures in the ISM of our Galaxy, they are significantly lower than those of known sites of dust formation such as the atmospheres of red giant stars ($nT \sim 10^{11}$ cm^{-3} K; Tielens 1990). At least in these cases, the alternative "evaporation flow" model (de Jong *et al.* 1990; Sparks 1992) —in which the gas and dust represent ISM brought in during a galaxy interaction— seems to be more appropriate. In this model, thermal interaction between the cool ISM and the hot gas both cools the hot gas locally (thus mimicking a cooling flow) while heating the cool ISM, giving rise to the observed optical and far-IR emission. Future quantitative analysis of these and new optical and X-ray data should allow us to make progress in distinguishing between these models.

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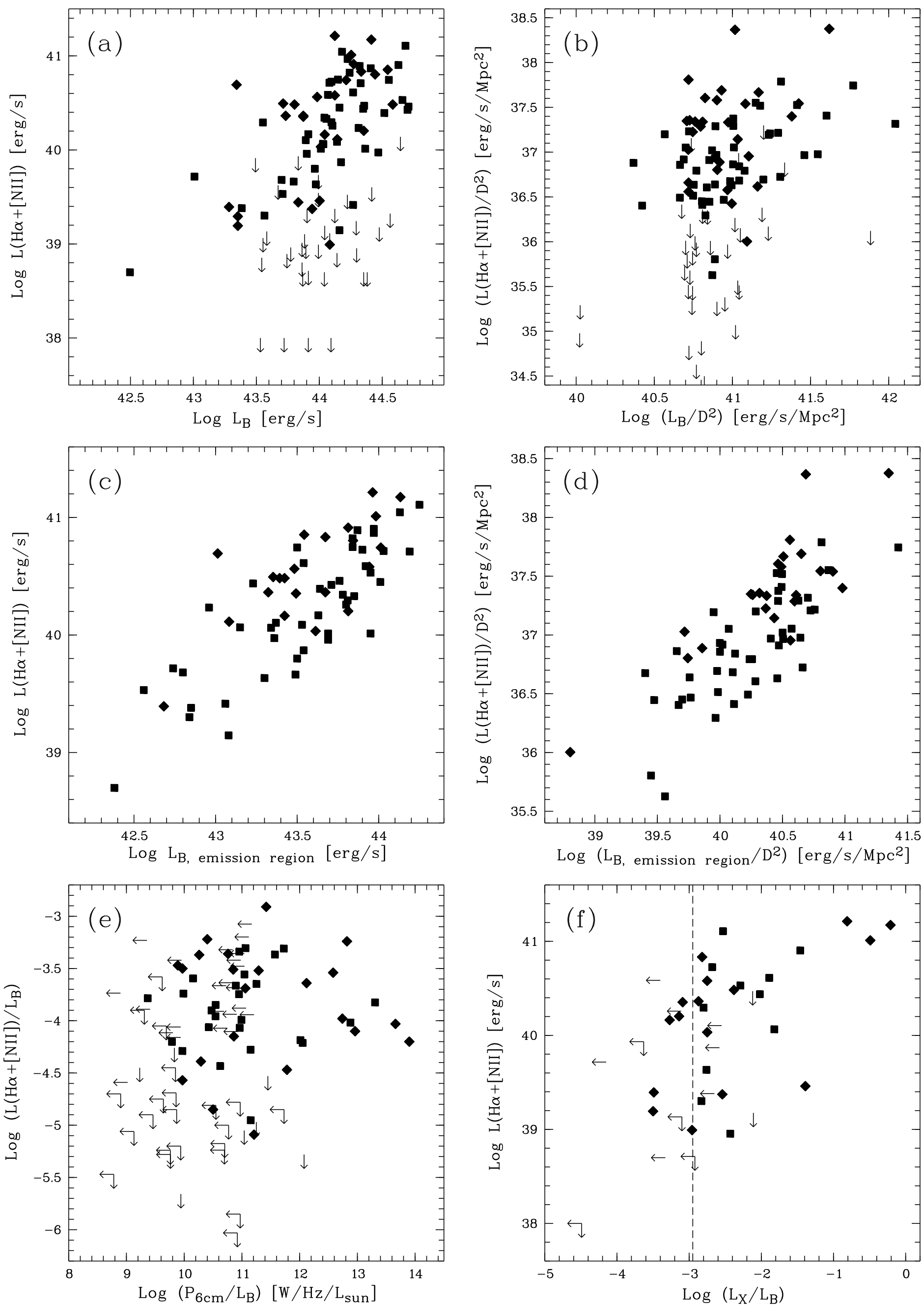

Figure 3. Correlations among ellipticals: **(a)** Hα+[N II] luminosity vs. total B-band luminosity; **(b)** Hα+[N II] flux vs. total B band flux; **(c)** Hα+[N II] luminosity vs. B-band luminosity emitted within the region occupied by the ionized gas; **(d)** Hα+[N II] flux vs. flux in B band emitted within the region occupied by the ionized gas; **(e)** Hα+[N II]-to-B-band luminosity ratio vs. ratio of total radio power at 6 cm over B-band luminosity; **(f)** Hα+[N II] luminosity vs. X-ray-to-blue luminosity ratio. The dashed line depicts the ratio L_X/L_B below which the X-ray emission is probably not primarily due to hot gas (Kim *et al.* 1992). **Symbols:** Filled squares are data on ellipticals from Macchetto *et al.* (1997) or Trinchieri & di Serego Alighieri (1991), and filled lozenges are data on ellipticals from Goudfrooij *et al.* (1994b).

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